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Experimental study of biomass gasification with oxygen-enriched air in fluidized bed gasifier

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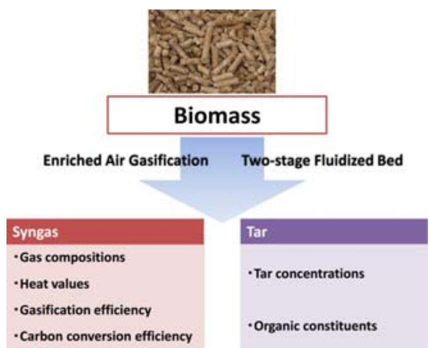
HIGHLIGHTS

- A new two-stage gasification process with oxygen-enriched air has been proposed to treat biomass.
- Gasification with enriched air is conducive to higher quality gas.
- Adding secondary oxygen leads to effectively remove of tar.

GRAPHICAL ABSTRACT



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ABSTRACT

Considering the universality, renewability and cleanness of biomass, an experimental research is carried out using rice straw in a two-stage fluidized bed. The experimental analysis identified the relevant parameters in the operation of the two-stage fluidized bed to investigate the properties of biomass enriched air gasification. Results show that higher gasification temperature is conducive to enhance the gasification performance. An increasing ER is shown to go against adding gas heat value. When oxygen concentration increases from 21% to 45%, the gas heating value increases from 4.00 MJ/kg to 5.24 MJ/kg and the gasification efficiency increases from 29.60% to 33.59%, which shows higher oxygen concentration is conducive to higher quality gas and higher gasification efficiency. A secondary oxygen injection leads to reduction of tar concentration from 15.78 g/Nm^3 to 10.24 g/Nm^3. The optimal secondary oxygen ratio is about 33.00%. When the secondary oxygen ratio increased to 46.86%, monocyclic aromatics reduced from 28.17% to 19.65% and PAHs increased from 34.97% to 44.05%, leading to the increase aromatization of tar.

1. Introduction

Due to overexploitation and irrational utilization of conventional energy, countries are actively looking for substitute of the normal regulations energy to solve the energy crisis. Biomass is included, which is the most promising renewable energy because of its huge production, storability and cleanness (Chen et al., 2004; Kuprianov et al., 2011).

According to United Nations Environment Programme, biomass has great potential to meet >65% demand of current worldwide energy (Qian, 2010). Global production of plant stalks from grain reach 1.7 billion tonnes per year, among which the global production of straw steadily increased from 200 million tonnes in 1960 to 740 million tonnes in 2014 (FAOSTAT Database, 2017). China is the world's largest producer of rice straw, which produces

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210 million tonnes to 310 million tonnes of rice straw from 210 million tonnes rice, accounted for 28% of global production of straw (Abraham et al., 2016). Straw production in China shows an increasing trend in the next 15 to 20 years. Only achieve the large-scale and intensive industrial production can we realize the recycling use of the vast straw resources.

In the research of biomass gasification, fluidized bed is widely used because of its wide adaptability, high efficiency of heat and mass transfer and large-scale scale-up. Because N_2 will cause the reduction of gas calorific value in air gasification, and using pure oxygen gasification can reduce the dilution effect of N_2 but increase the cost of commercial operation. So comparing the two kinds of gasification, the oxygen-enriched air gas with the oxygen concentration of 30% produced by membrane separation is more desirable, which can reduce costs while improve the quality of gasification gas. Huynh and Kong (2013), Lenis et al. (2016) and Yu et al. (2013) carried out the research of biomass gasification in fluidized bed, fixed bed and entrained bed using low concentration oxygen-enriched air, however, there are few reports about oxygen-enriched air gasification, especially in fluidized bed.

In the process of biomass gasification, tar is an inevitable byproduct. Tar exists in gaseous state in high temperature, uniformly mixed with the gas products. However, at a low temperature (<200 °C), tar is easy to condense and bond together with water and char, blocking gas pipeline which result in difficulties of gasification equipment operating (Devi et al., 2005). Furthermore, tar produced in biomass gasification accounts for 5% to 15% energy of the total biogas energy, whose energy is difficult to be efficiently used with the biogas at low temperature, leading to reduction of gasification efficiency. In order to solve the problem of tar, adding a secondary oxygen is a possible way, which has the function to increase the space temperature in the dilute phase area and promote the secondary cracking of tar. Galindo et al. (2014) carried out a research about air gasification in a two-stage downdraft fixed bed, and the results showed that the temperature of the furnace increased when the two-stage model was conducted. Sulc et al. (2012) carried out a two-stage air gasification experiment using sawdust particles, and analysed the composition and content of tar. The results showed the contents of typical aromatics in tar decreased. However, there are few studies on two-stage fluidized bed, especially in the aspect of oxygen-enriched air gasification.

Therefore, in order to study the gas production characteristics and tar characteristics of biomass in two-stage oxygen-enriched air gasification, the thesis selected rice straw to conduct a two-stage fluidized bed with the primary air of oxygen-enriched air and the secondary oxygen of pure oxygen. The experimental analysis identified the relevant parameters in the operation of the two-stage fluidized bed to investigate the properties of biomass enriched-air gasification.

2. Experimental part

2.1. Experimental materials and bed materials

The raw materials were the rice straw in Jiangsu province, which had been crushed and screened to particle diameter of 0.5 mm to 2 mm. Its proximate analysis and ultimate analysis are shown in Table 1. The bed materials were high alumina bauxite with particle size from 0.18 mm to 0.25 mm.

Table 1
Proximate and ultimate analysis of rice straw.

	Proximate analysis (wt% on received basis)				Ultimate analysis (wt% on received basis)				
	M	V.	A	FC	C	H	N	S	O
Rice straw	7.95	59.58	13.73	18.74	40.83	4.91	1.14	0.19	31.26

2.2. Experimental equipments

The experiment equipments can be divided into five parts, containing the gas supply system, feeding system, gasification reactor, gas purification system and sampling system, as shown in Fig. 1.

Gas supply system mainly consists of an air compressor, an oxygen cylinder, an air preheater, rotameters and gas pipelines, etc. Feed system includes a hopper with an agitator and a screw feeder. The screw feeder is equipped with a motor to control the speed of the screw. By changing the frequency of motor, the feed rate is set. In order to prevent the thermal deformation of the screw, a water-cooled bushing is equipped outside it. Gasification reactor is a bubbling fluidized bed with 50 mm inner diameter and 1.2 m height, which equipped with an air distribution plate at bottom to even the distribution of wind. High temperature resistance furnace is added on lateral face of the reactor. The furnace controls the temperature by the temperature controller. The reactor is covered by heat insulation materials to ensure the maximum design operating temperature 1100 °C. Gas purification system includes a cyclone separator, a straight condenser, a fiberglass dust filter, absorb bottles with isopropyl alcohol, absorb bottles with silica gel, low temperature region with ethanol added in dry ice and gas pipes. By cooling and filtrating, gas tar is isolated and gas becomes clean. Sampling system consists of a gas meter, vacuum pumps, collection bags and a MRU gas analyzer.

2.3. Procedures

After removing residual ashes in the connecting pipes and the cyclone separator, add pre-screened bed materials in the gasifier and pour crushed raw materials into the hopper to seal the inlet. Open the import tap of the water-cooled bushing and adjust the PID temperature controllers to select electric furnace heating rate and final gasification temperature. Turn on the temperature controllers of the air preheater and the cyclone separator and set them in a selected temperature of 400 °C and 200 °C. When the temperature remains stable, it is able to adjust the frequency of screw feeder and the flow rate of air. Remaining the flow rate of gasification agent unchanged, we change the feed rate to acquire different equivalence ratio (ER).

When the experiments were conducted with secondary oxygen, considering the disadvantage of much inert gas nitrogen in air, 99% purity oxygen provided by cylinder was selected as secondary oxygen. Keep the flow of primary enriched-air constant to maintain the dense-phase zone in good fluidized state and adjust the flow of secondary oxygen and the feed rate to achieve the change of secondary oxygen ratio (SOR), which is defined as:

$$\mathrm{SOR} = \frac{\mathrm{O_2\ inlet\ at\ the\ second\ stage}}{\mathrm{O_2\ inlet\ at\ the\ whole\ stage}}(\mathrm{w/w})$$

The main parameters of the gasification process are defined as follows:

Gas calorific value:

$$\mathrm{LHV} = 0.001 \times 4.2(30\varphi(\mathrm{CO}) + 25.7\varphi(\mathrm{CO_2}) + 84.5\varphi(\mathrm{CO_4}))\left(\mathrm{MJ/Nm^3}\right)$$

Gas yield:

$$G_p = \frac{q_v}{q_m}\left(\mathrm{Nm^3/kg}\right)$$

Gasification efficiency:

$$\eta_c = \frac{12G_p(\varphi(\mathrm{CO}) + \varphi(\mathrm{CO_2}) + \varphi(\mathrm{CO_4})) \times \mathrm{LHV}}{22.4 \times \mathrm{C}} \times 100\%$$